THE UNIVERSITY of ADELAIDE

GAMBIT

(Global and Modular BSM Inference Tool)

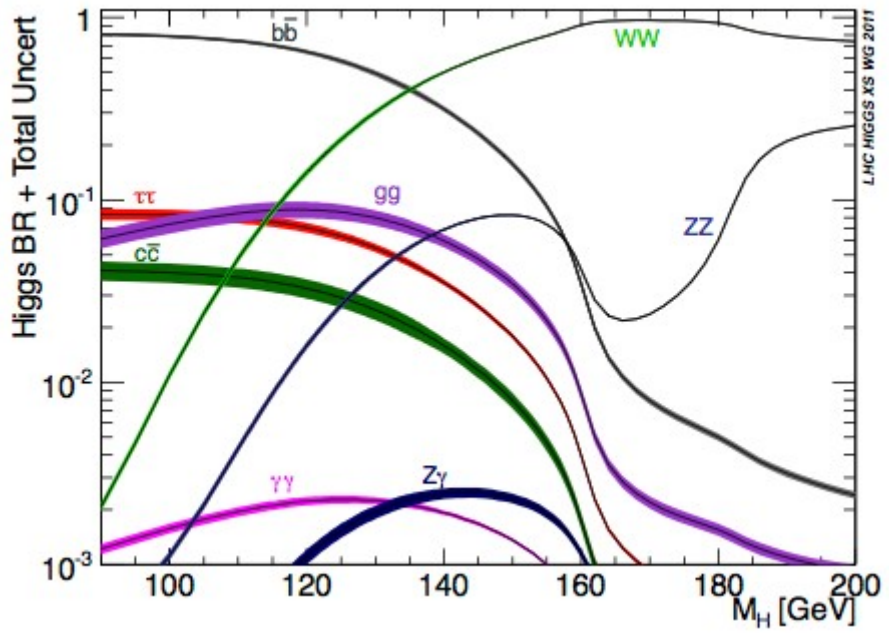
Martin White

CoEPP Glenelg workshop 2017

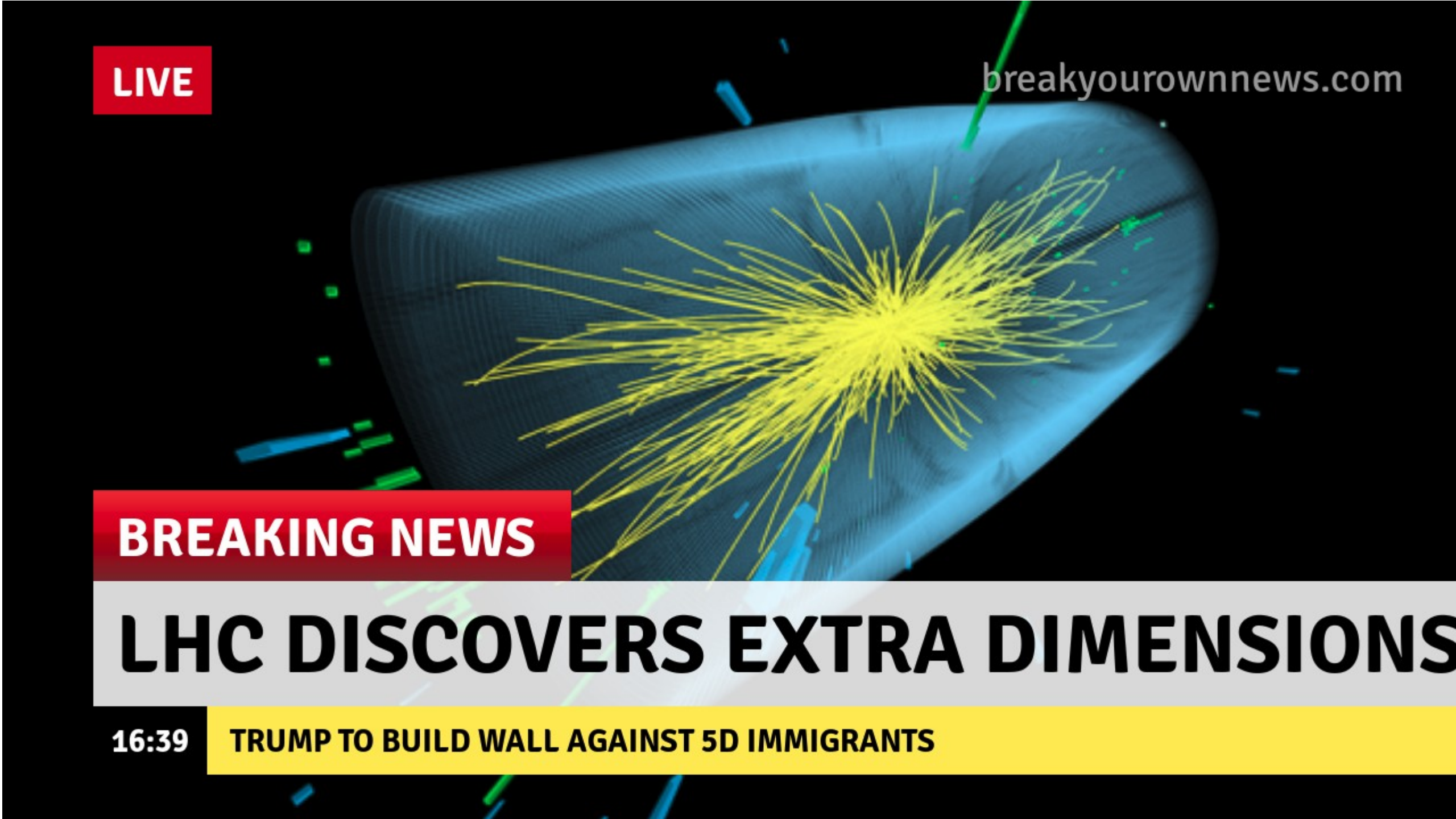
The Higgs discovery in 2012 gave us:

- The last piece of the SM
- The last occasion when we could unambiguously tell what a collider has discovered

What happens if the LHC sees a dramatic missing energy signature?




LIVE
breakyourownnews.com
BREAKING NEWS
LHC DISCOVERS SUPERSYMMETRY
16:36
GORDON KANE "PREDICTED MASS SPECTRUM IN 2003"


LIVE
breakyourownnews.com
BREAKING NEWS
LHC DISCOVERS EXTRA DIMENSIONS
16:39
TRUMP TO BUILD WALL AGAINST 5D IMMIGRANTS


LIVE
breakyourownnews.com
BREAKING NEWS
LHC DISCOVERS DARK MATTER
10:33
EXCEPT IT MIGHT NOT BE: WE ONLY KNOW IT IS STABLE ON DETECTOR TIMESCALES

Possible discoveries and assumptions

- We might discover something decaying visibly:

Default assumption: something to do with EWSB

- We might discover something decaying (semi-) invisibly

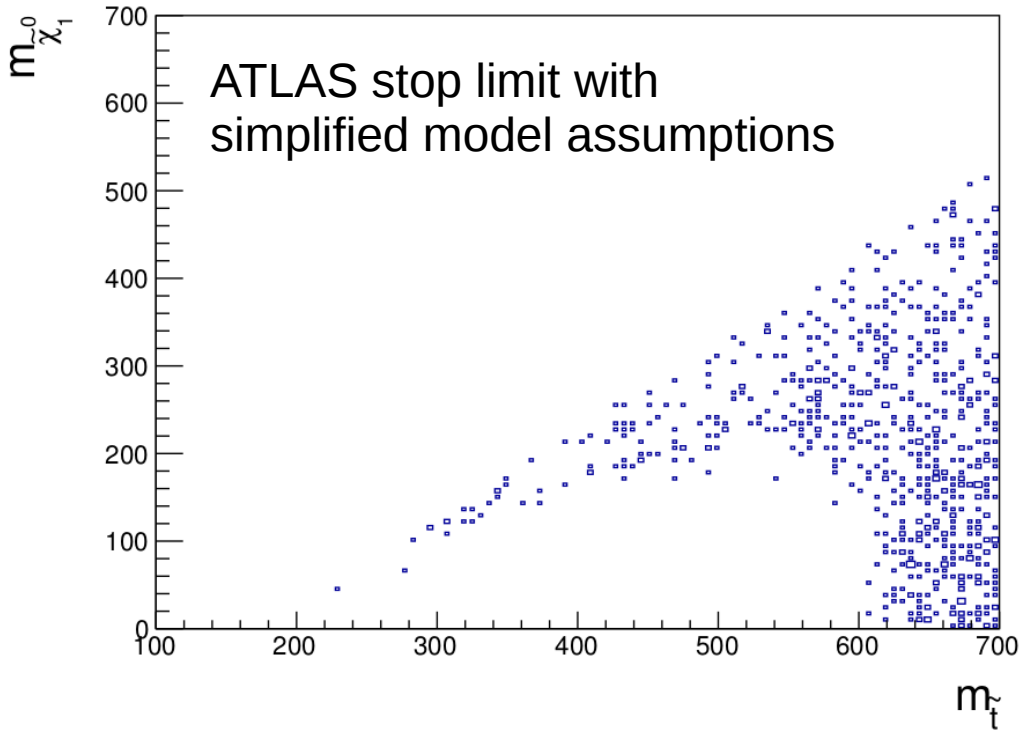
Default assumption: something to do with DM

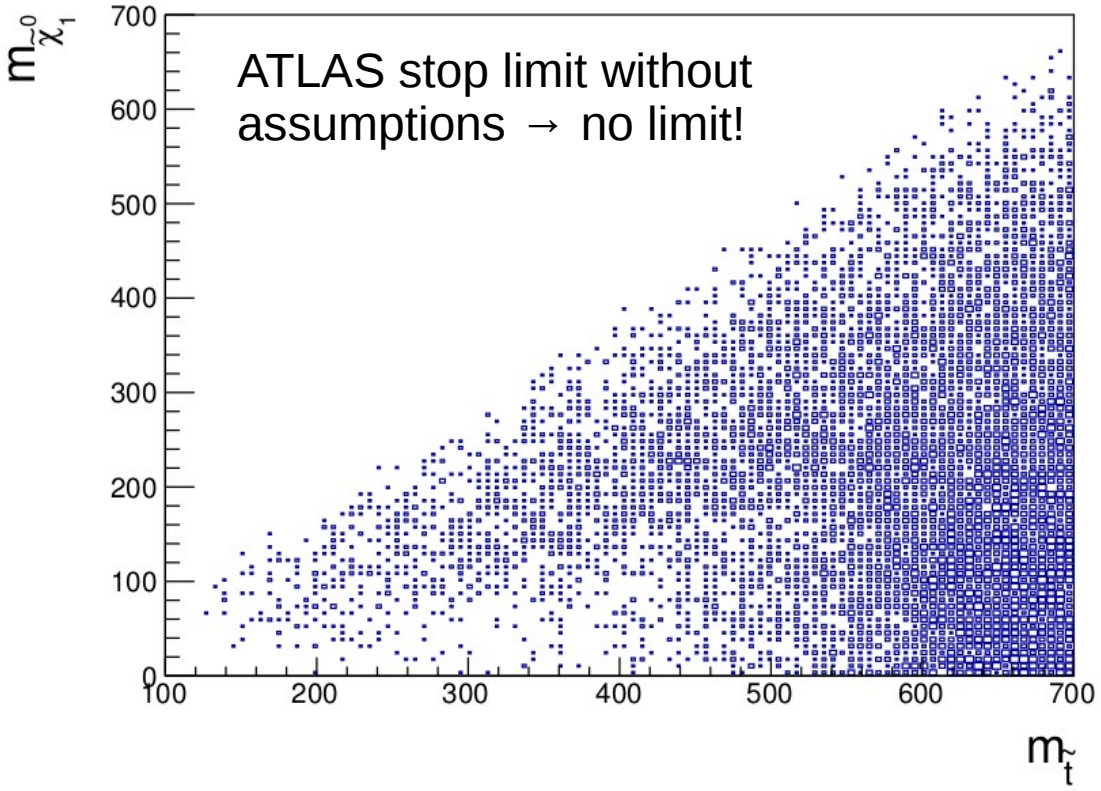
- We might discover nothing extra at all at the LHC

How do we make further progress?

What about LHC non-discoveries?

- They tell us a lot, but are infamously hard to reinterpret – how should we do that?





The answer: use as much data as possible

- Combine ATLAS+CMS null and positive results to test specific theories
- Don't forget LHCb!
- Don't forget other experiments...

Other experiments

- low-energy accelerators
- measurements of the magnetic moment of the muon
- beam dump/fixed target
- electroweak precision tests
- dark matter direct detection experiments
- searches for antimatter in cosmic rays
- nuclear cosmic ray ratios
- radio astronomy data
- effects of dark matter on reionisation, recombination and helioseismology
- the observed dark matter cosmological abundance
- neutrino masses and mixings
- gamma ray searches (e.g. FERMI-LAT, HESS, CTA, etc)

How to combine data

- Correct answer is to use a global statistical fit
- Frequentist or Bayesian methods available

Parameter estimation

Given a particular model, which set of parameters best fits the available data

(Rigorous exclusion limits and parameter measurements)

Model comparison

Given a set of models, which is the best description of the data, and how much better is it?

(Model *X* is now worse than model *Y*)

The dream

Global fit results

- Recent years have seen an explosion of tools that make study of user-defined Lagrangians easier

  - e.g. Feynrules → Madgraph, CalcHEP → Micromegas, MadDM, NLOCT + much, much more

- Even so, a general global fit tool requires some very tricky innovations:

  - calculations are not allowed to know about Lagrangian parameters – how do you do that?
  - how do you make an easy interface for tying existing code together?
  - how do you store parameters in a scale independent way, but reintroduce scales in calculations?
  - how do you make LHC constraints model independent?
  - how do you make astrophysical constraints model independent?
  - ***how do we do all of this fast enough to get convergence within the age of the universe?***

GAMBIT: The Global And Modular BSM Inference Tool

gambit.hepforge.org

- Fast definition of new datasets and theoretical models
- Plug and play scanning, physics and likelihood packages
- Extensive model database – not just SUSY
- Extensive observable/data libraries
- Many statistical and scanning options (Bayesian & frequentist)
- *Fast* LHC likelihood calculator
- Massively parallel
- Fully open-source

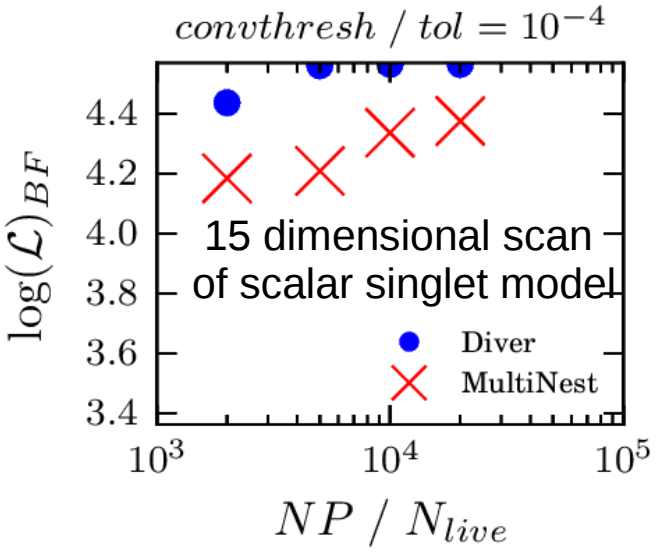
ATLAS	A. Buckley, P. Jackson, C. Rogan, M. White
LHCb	M. Chrząszcz, N. Serra
Belle-II	F. Bernlochner, P. Jackson
Fermi-LAT	J. Conrad, J. Edsjö, G. Martinez, P. Scott
CTA	C. Balázs, T. Bringmann, J. Conrad, M. White
HESS	J. Conrad
IceCube	J. Edsjö, P. Scott
XENON/DARWIN	J. Conrad, B. Farmer, R. Trotta
Theory	P. Athron, C. Balázs, T. Bringmann, J. Cornell, J. Edsjö, B. Farmer, A. Fowlie, T. Gonzalo, J. Harz, S. Hoof, F. Kahlhoefer, A. Kvellestad, F.N. Mahmoudi, J. McKay, A. Raklev, R. Ruiz, P. Scott, R. Trotta, C. Weniger, M. White, S. Wild

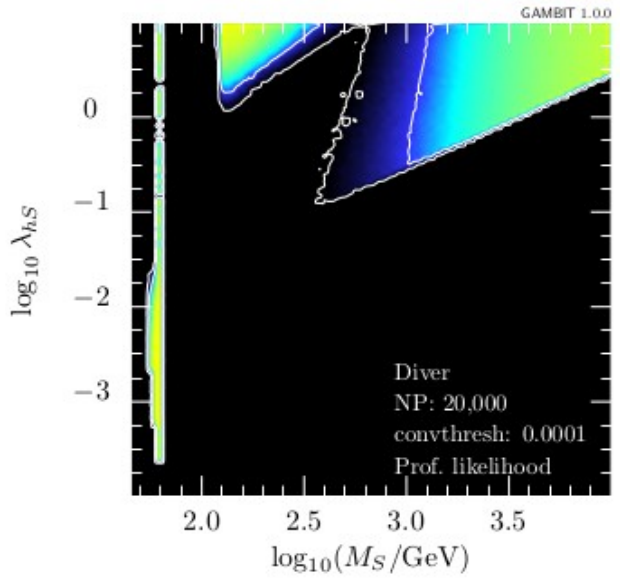
29 Members, 9 Experiments, 5 major theory codes, 11 countries

Global

- Complete global statistical fit framework
- Can be Bayesian, Frequentist or other (random, grid, etc)
- Interfaced to the best + fastest scanners available:

  Multinest, MCMC, Diver (new differential evolution scanner)

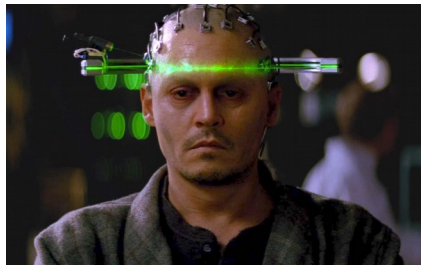




Publication ready plots available using *pippi* plotting code on the GAMBIT HDF5 output

Global and Modular

- **ColliderBit:** collider observables including Higgs + SUSY Searches from ATLAS, CMS, LEP
- **DarkBit:** dark matter observables (relic density, direct & indirect detection)
- **FlavBit:** including $g-2$, $b \to s\gamma$, B decays (new channels), angular obs., theory unc., LHCb likelihoods
- **SpecBit:** generic BSM spectrum object, providing RGE running, masses, mixings
- **DecayBit:** decay widths for all relevant SM and BSM particles
- **PrecisionBit:** precision EW tests (mostly via interface to FeynHiggs or SUSY-POPE)
- **ScannerBit:** manages stats, sampling and optimisation



What's in a module?

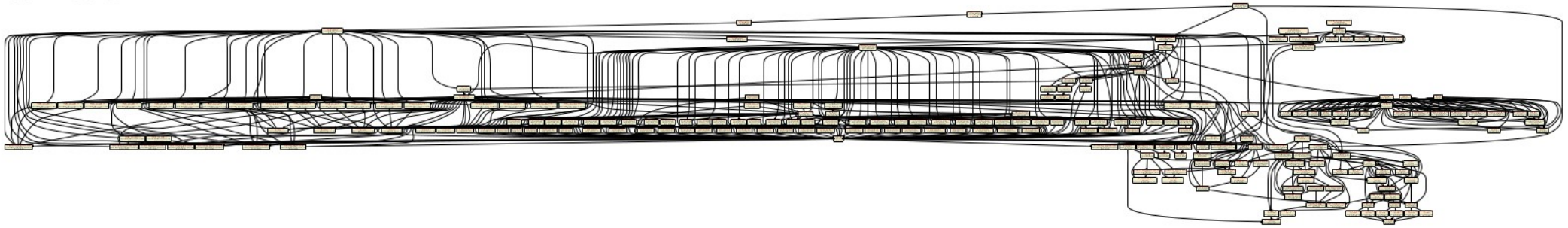
- Module functions (actual bits of GAMBIT C++ code)
- These can depend on other module functions
- Or can they can depend on *backends*(external codes)
- Adding new things is ***easy*** (detailed manual)
- Hooking up new backends or swapping them is ***easy***
- Module functions are **tagged** according to what they can calculate → plug and play!

How does GAMBIT work?

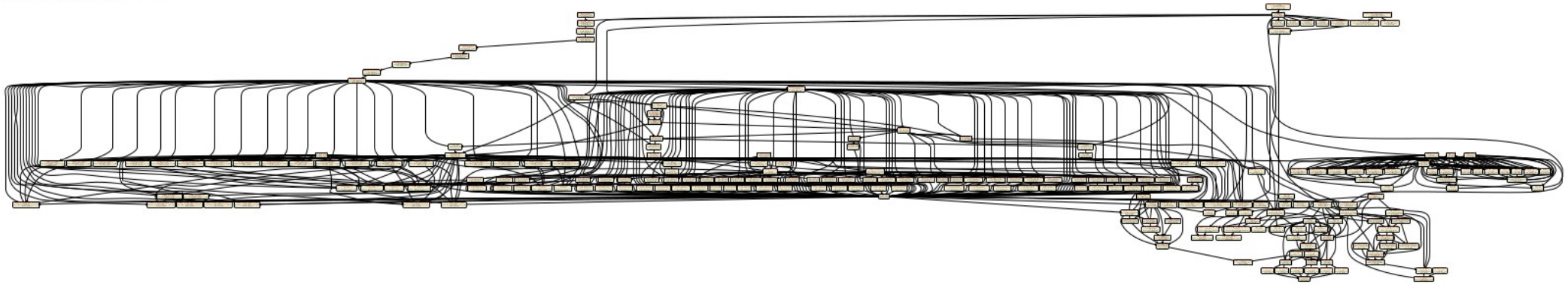
- You specify what to calculate and how (yaml input file)
- GAMBIT checks to see which functions can do it
- A dependency resolver stitches things together in the right order, and calculations are also ordered by speed
- GAMBIT performs the scan and writes output
- Pippi makes the plots
- You(r student) write(s) the paper

Dependency resolution in action

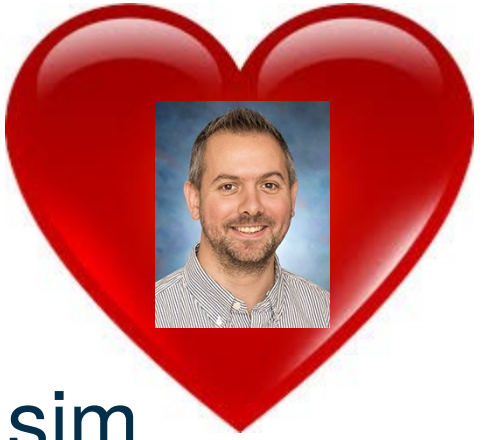
CMSSM:



MSSM7:



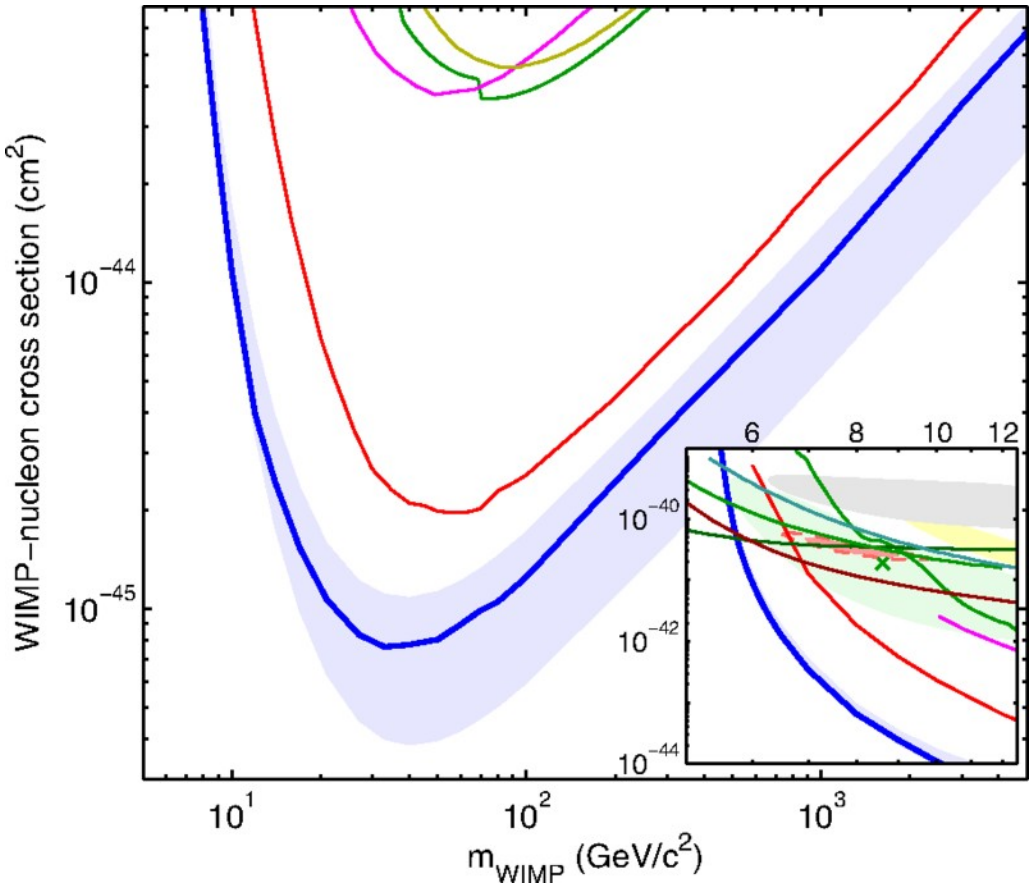
Model independent LHC limits

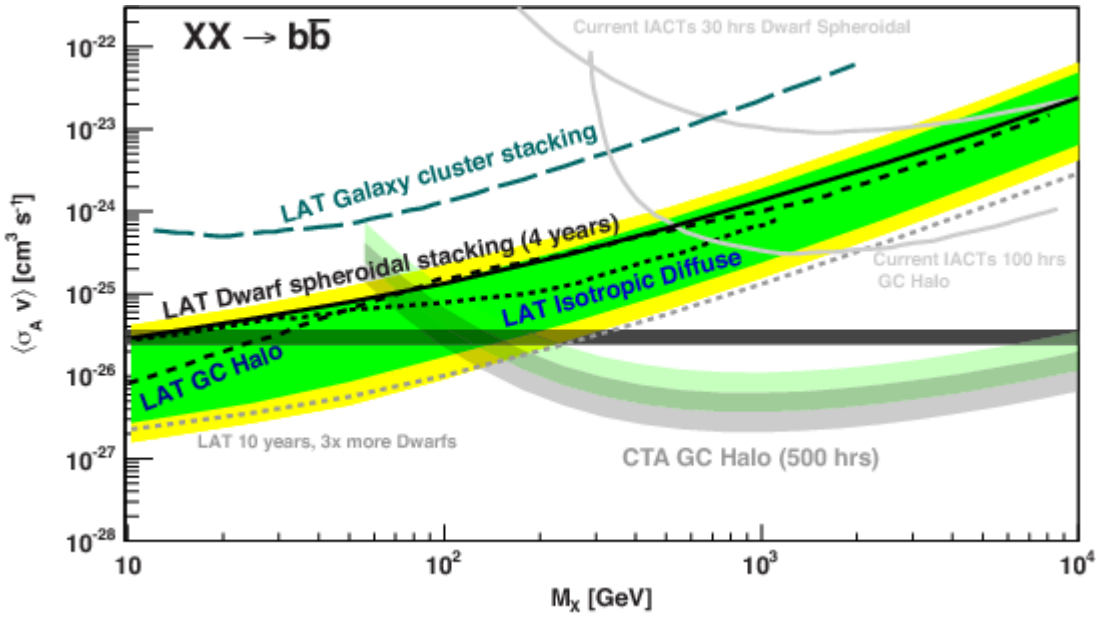


- Custom parallelised Pythia MC + custom detector sim
- Can generate 20,000 events on 12 cores in < 5 s
- Then apply Poisson likelihood with nuisance parameters for systematics
- Combine analyses using best expected exclusion
- The best you can do without extra public info from the experiments. CMS are getting better at this:

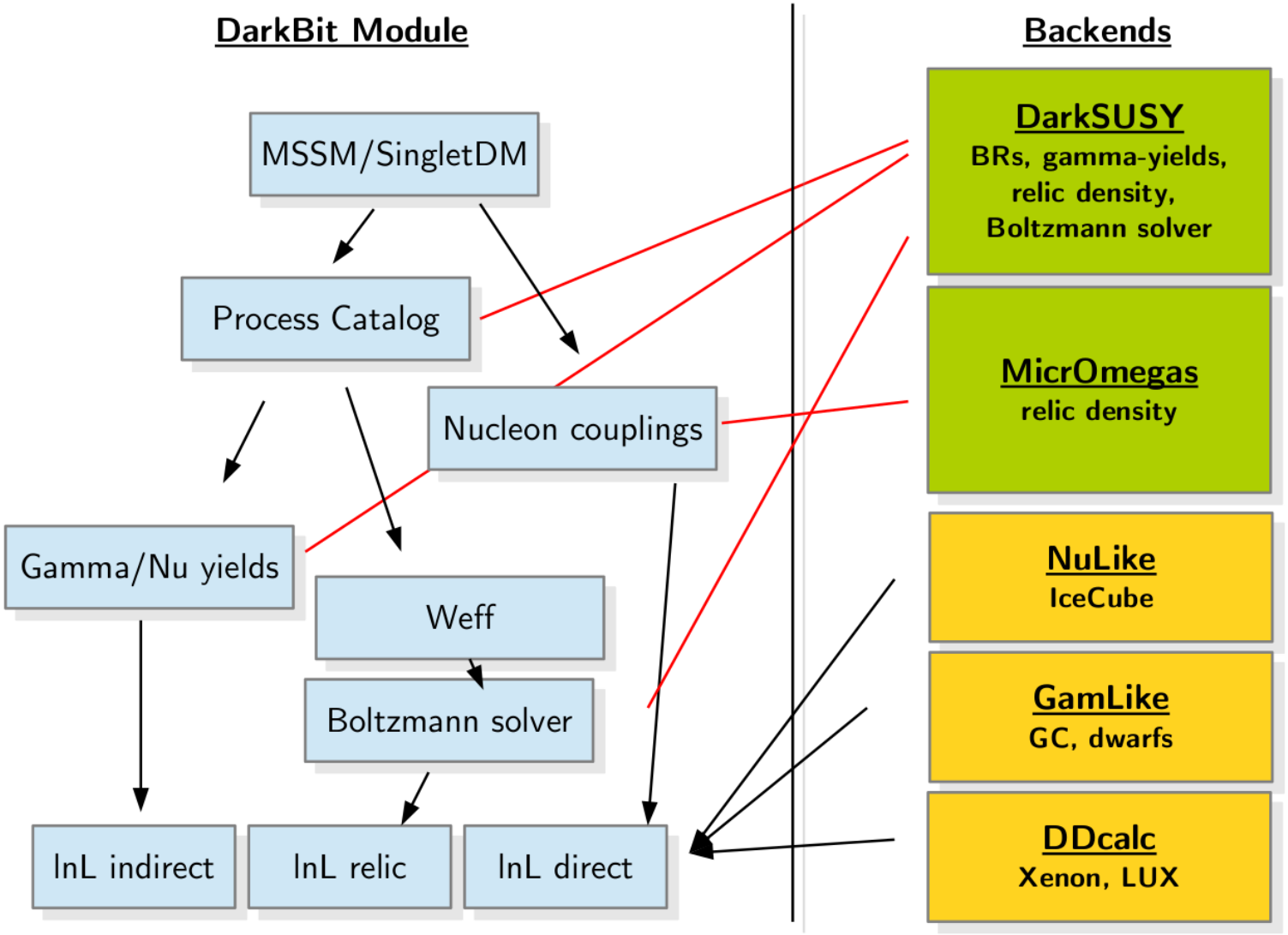
  https://cds.cern.ch/record/2242860/files/NOTE2017_001.pdf

Astro limits: the problem





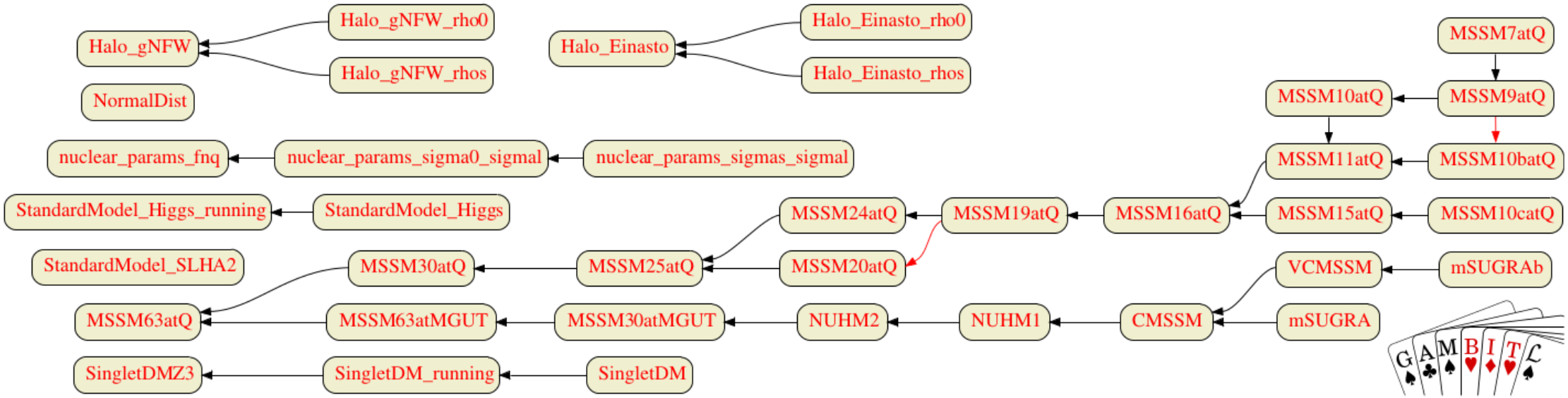
Astro limits: the GAMBIT solution



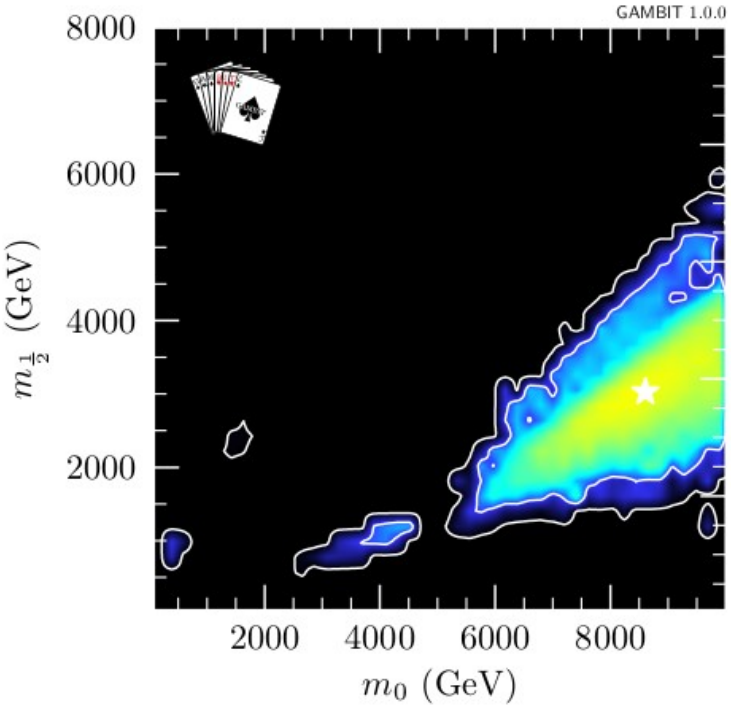
- **Event level neutrino telescope and gamma ray likelihoods!**
- **First principles treatment of direct search limits → easily extendable to non-trivial operators**
- **Very large range of experiments included (includes future, e.g. CTA)**

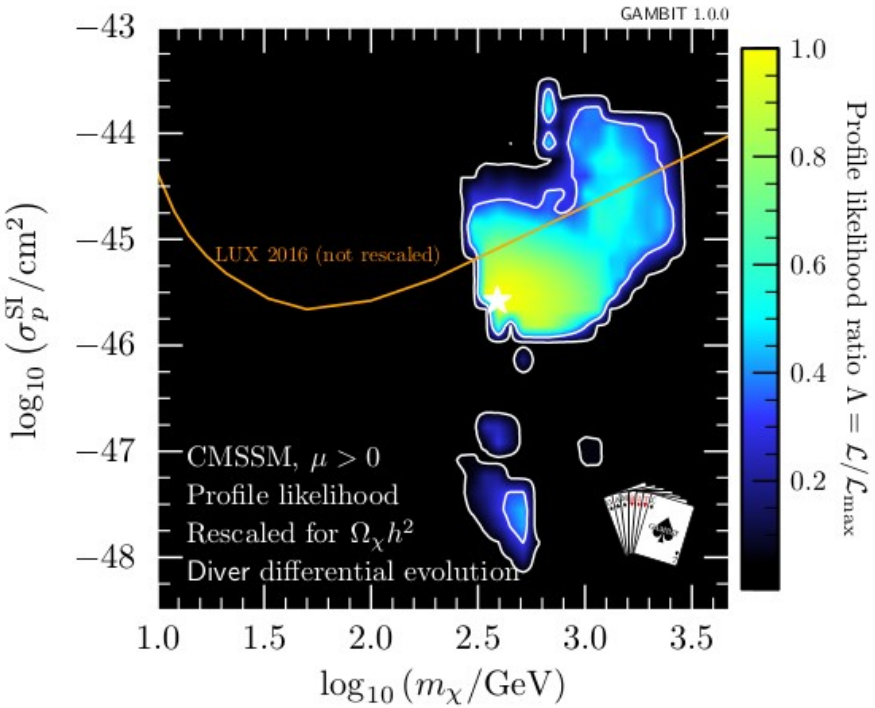
Global and Modular BSM

- Models are defined by their parameters and relations to each other
- Models can inherit from parent models, easy translation between relations
- We have so far scanned SUSY + Higgs portal + axion + two Higgs doublet models



Global and Modular BSM Inference

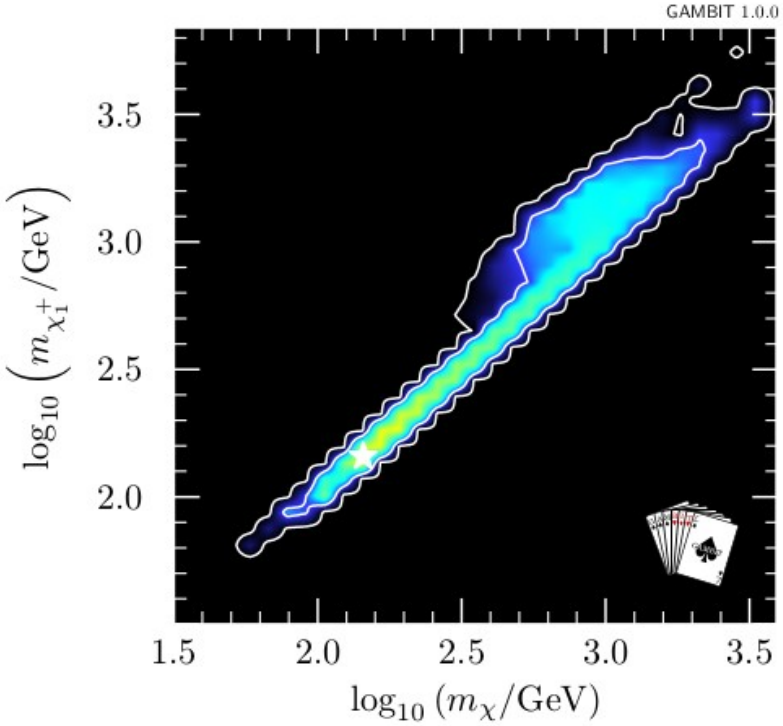


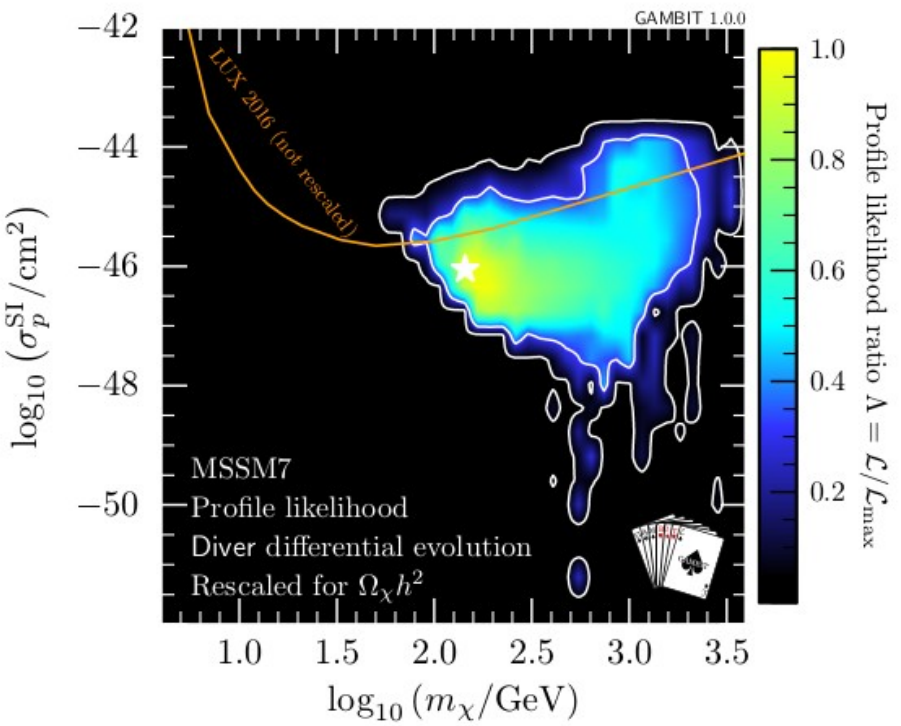


CMSSM
(also NUHM1 and NUHM2)

- m_0, $m_{\frac{1}{2}}$, A_0, $\tan\beta$ + 5 nuisances
- H/A^0 funnel, $\chi^\pm$ co-annihilation, $\tilde{\tau}$ co-annihilation, $\tilde{t}$ co-annihilation
- Includes LUX 2016, Panda-X + direct simulation of all relevant LHC Run 1 limits. Run 2 coming soon.

Global and Modular BSM Inference

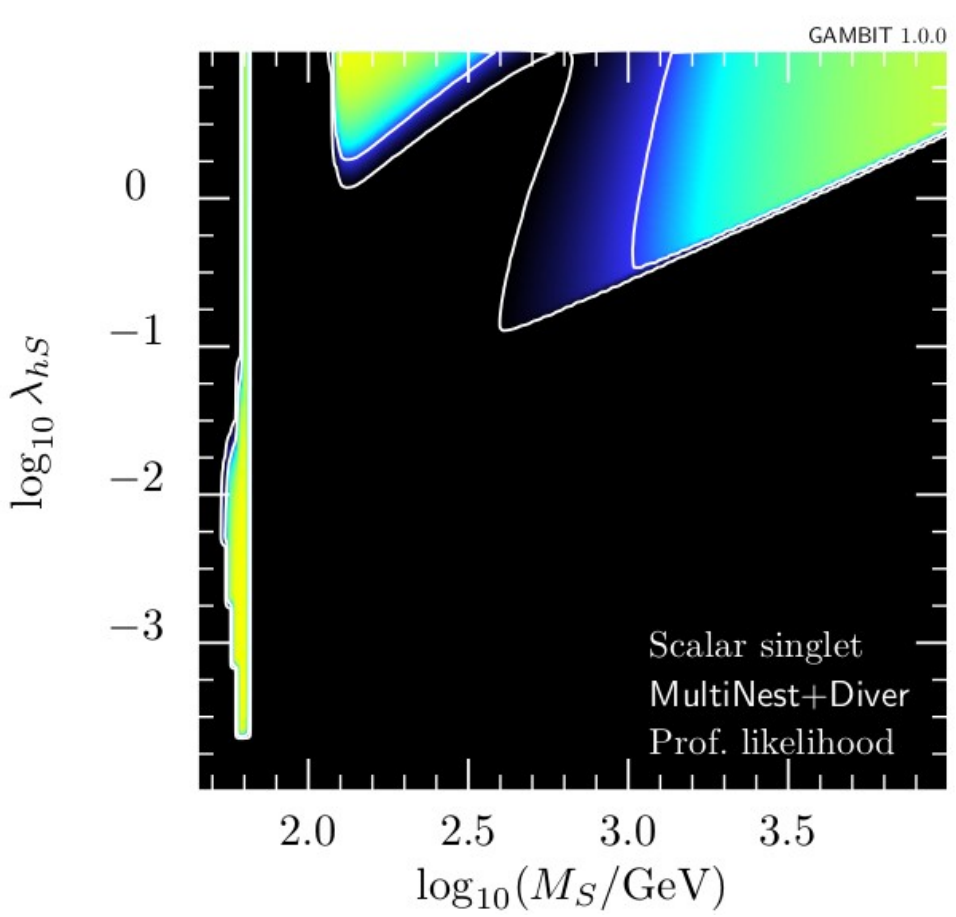


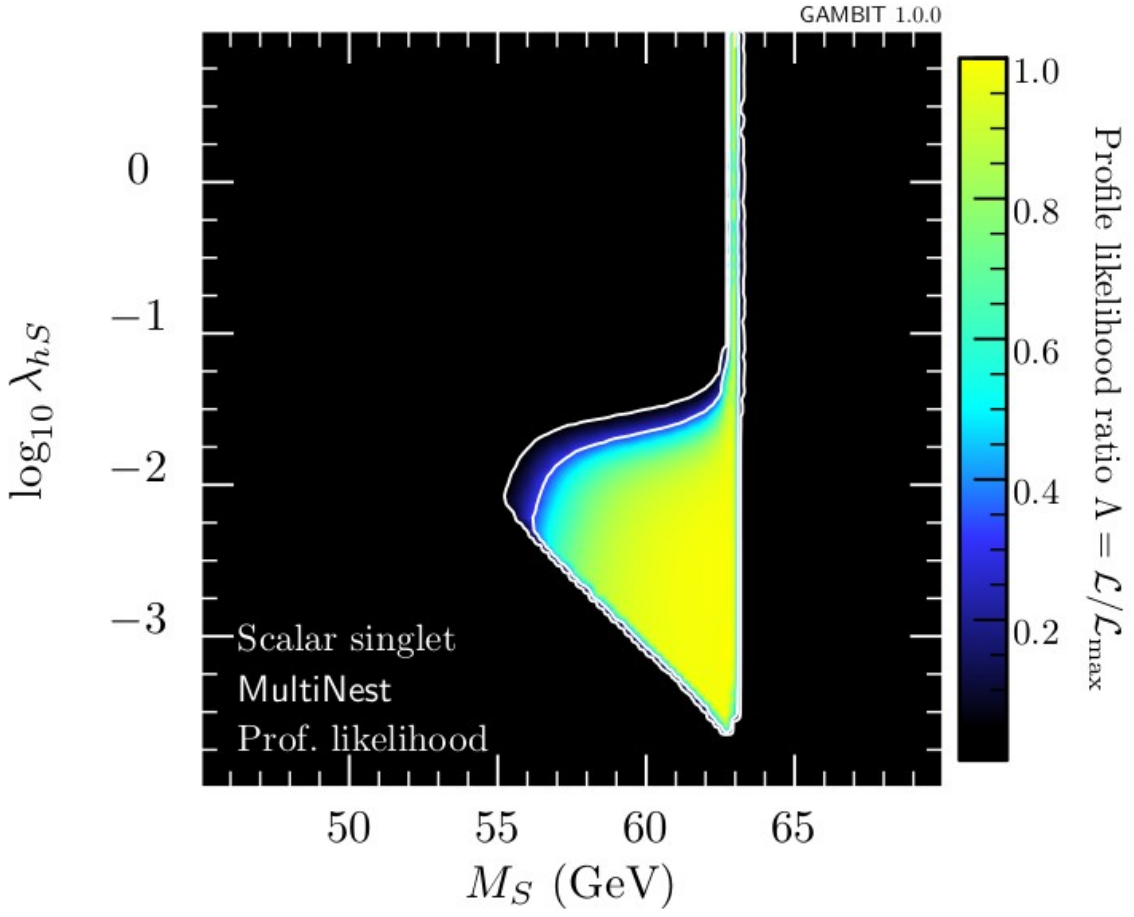


MSSM7

- $m_{\tilde{f}}$, M_2, A_u, A_d, m_{Hu}, m_{Hd}, $\tan\beta$ + 5 nuisances
- H/A^0 funnel, h/Z funnel, $\chi^\pm$ co-annihilation, $\tilde{\tau}$ co-annihilation, $\tilde{t}/\tilde{b}$ co-annihilation
- Includes LUX 2016, Panda-X + direct simulation of all relevant LHC Run 1 limits. Run 2 coming soon.

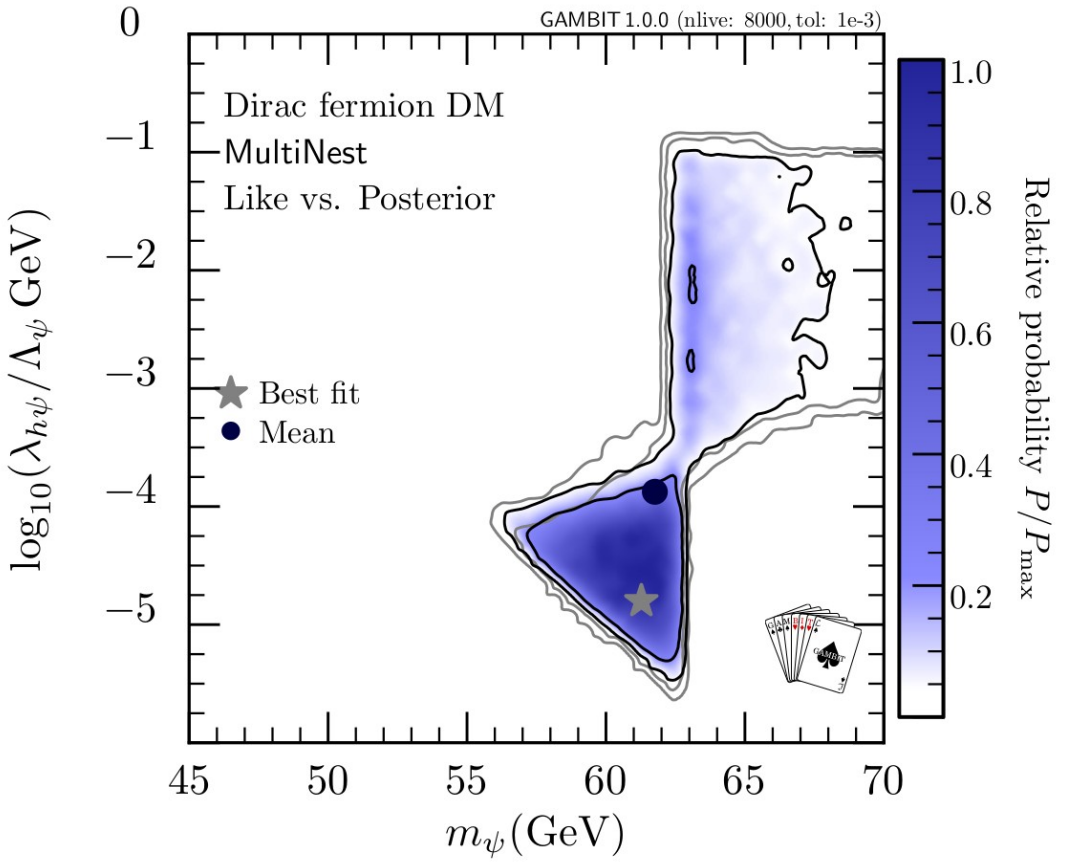
Global and Modular BSM Inference

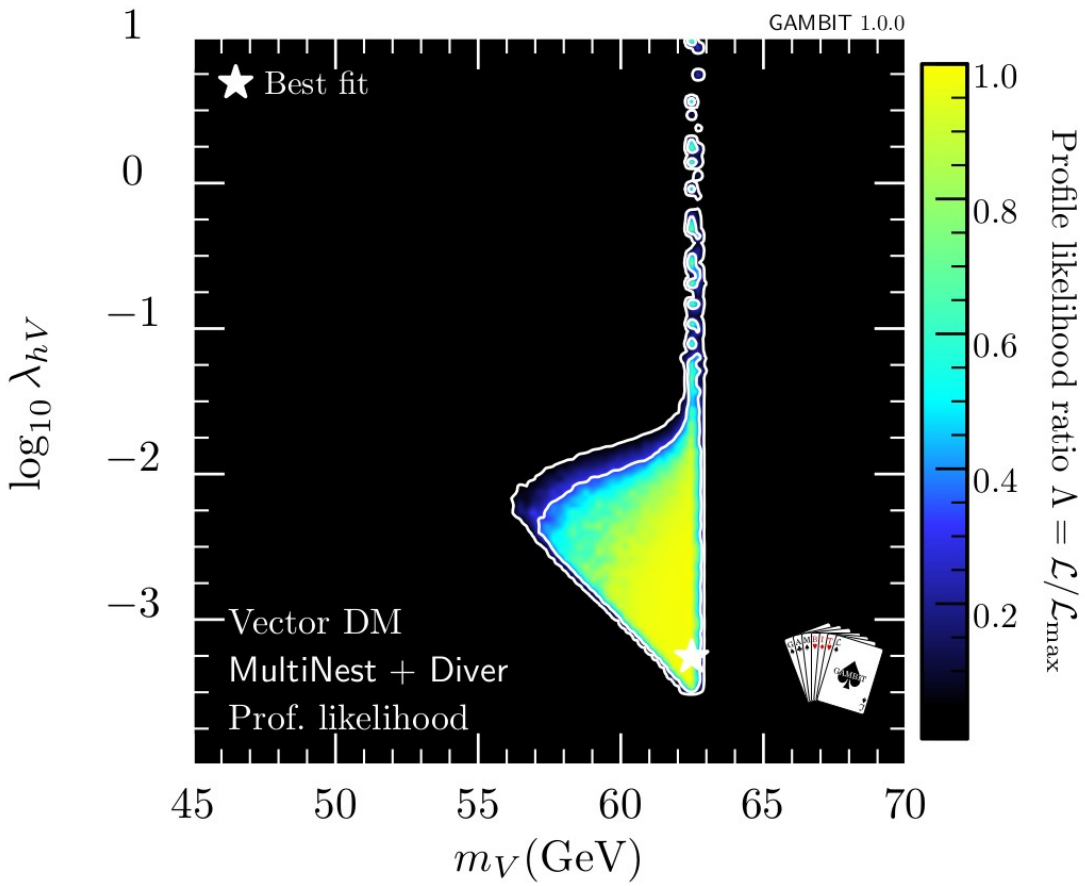




Scalar singlet DM (m_s, λ_{hs} + 13 nuisances)

Global and Modular BSM Inference

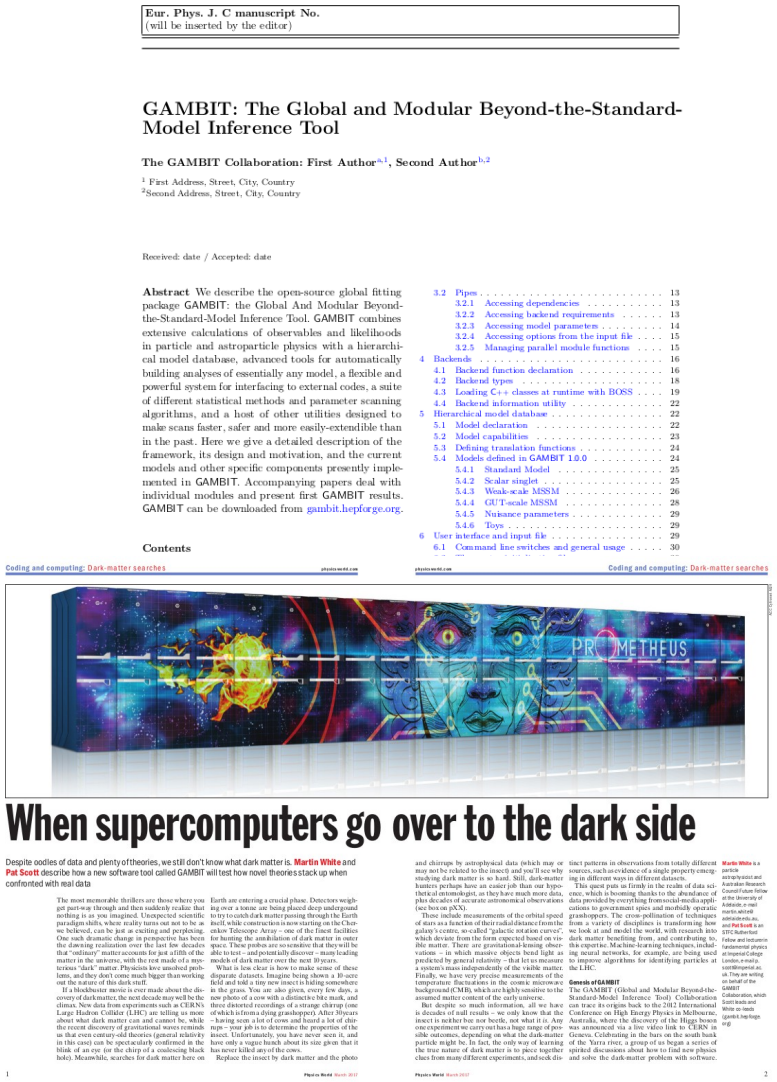




Fermion and vector DM Higgs portal (Ankit Beniwal)

Global and Modular BSM Inference Tool

- GAMBIT will be released next month as an ***open source public tool***
- 9 papers to be published in EPJC (design, manual + first physics results)
- Feature article in *Physics World* March 2017 issue if you want a gentler introduction
- Talks lined up with ATLAS physics groups



Eur. Phys. J. C manuscript No.
(will be inserted by the editor)

GAMBIT: The Global and Modular Beyond-the-Standard-Model Inference Tool

The GAMBIT Collaboration: First Author[a,1], Second Author[b,2]

[1] First Address, Street, City, Country
[2] Second Address, Street, City, Country

Received: date / Accepted: date

Abstract We describe the open-source global fitting package GAMBIT: the Global And Modular Beyond-the-Standard-Model Inference Tool. GAMBIT combines extensive calculations of observables and likelihoods in particle and astroparticle physics with a hierarchical model database, advanced tools for automatically building analyses of essentially any model, a flexible and powerful system for interfacing to external codes, a suite of different statistical methods and parameter scanning algorithms, and a host of other utilities designed to make scans faster, safer and more easily-extendible than in the past. Here we give a detailed description of the framework, its design and motivation, and the current models and other specific components presently implemented in GAMBIT. Accompanying papers deal with individual modules and present first GAMBIT results. GAMBIT can be downloaded from gambit.hepforge.org.

Contents

physicsworld.com Coding and computing: Dark-matter searches

When supercomputers go over to the dark side

Despite oodles of data and plenty of theories, we still don't know what dark matter is. **Martin White** and **Pat Scott** describe how a new software tool called GAMBIT will test how novel theories stack up when confronted with real data

The most memorable thrillers are those where you get part-way through and then suddenly realize that nothing is as you imagined. Unexpected scientific paradigm shifts, where reality turns out not to be as we believed, can be just as exciting and perplexing. One such dramatic change in perspective has been the dawning realization over the last few decades that "ordinary" matter accounts for just a fifth of the matter in the universe, with the rest made of a mysterious "dark" matter. Physicists love unsolved problems, and they don't come much bigger than working out the nature of this dark stuff.

If a blockbuster movie is ever made about the discovery of dark matter, the next decade may well be the climax. New data from experiments such as CERN's Large Hadron Collider (LHC) are telling us more about what dark matter can and cannot be, while the recent discovery of gravitational waves reminds us that even century-old theories (general relativity in this case) can be spectacularly confirmed in the blink of an eye (or the chirp of a coalescing black hole). Meanwhile, searches for dark matter here on Earth are entering a crucial phase. Detectors weighing over a tonne are being placed deep underground to try to catch dark matter passing through the Earth itself, while construction is now starting on the Cherenkov Telescope Array – one of the finest facilities for hunting the annihilation of dark matter in outer space. These probes are so sensitive that they will be able to test – and potentially discover – many leading models of dark matter over the next 10 years.

What is less clear is how to make sense of these disparate datasets. Imagine being shown a 10-acre field and told a tiny new insect is hiding somewhere in the grass. You are also given, every few days, a new photo of a cow with a distinctive bite mark, and three distorted recordings of a strange chirrup (one of which is from a dying grasshopper). After 30 years – having seen a lot of cows and heard a lot of chirrups – your job is to determine the properties of the insect. Unfortunately, you have never seen it, and have only a vague hunch about its size given that it has never killed any of the cows.

Replace the insect by dark matter and the photo and chirrups by astrophysical data (which may or may not be related to the insect) and you'll see why studying dark matter is so hard. Still, dark-matter hunters perhaps have an easier job than our hypothetical entomologist, as they have much more data, plus decades of accurate astronomical observations (see box on p[XX]).

Those include measurements of the orbital speed of stars as a function of their radial distance from the galaxy's centre, so-called "galactic rotation curves", which deviate from the form expected based on visible matter. There are gravitational-lensing observations – in which massive objects bend light as predicted by general relativity – that let us measure a system's mass independently of the visible matter. Finally, we have very precise measurements of the temperature fluctuations in the cosmic microwave background (CMB), which are highly sensitive to the assumed matter content of the early universe.

But despite so much information, all we have is decades of null results – we only know that the insect is neither bee nor beetle, not what it is. Any one experiment we carry out has a huge range of possible outcomes, depending on what the dark-matter particle might be. In fact, the only way of learning the true nature of dark matter is to piece together clues from many different experiments, and seek distinct patterns in observations from totally different sources, such as evidence of a single property emerging in different ways in different datasets.

This quest puts us firmly in the realm of data science, which is booming thanks to the abundance of data provided by everything from social-media applications to government spies and mobbish spatiotemporal grasshoppers. The cross-pollination of techniques from a variety of disciplines is transforming how we look at and model the world, with research into dark matter benefiting from, and contributing to, this expertise. Machine-learning techniques, including neural networks, for example, are being used to improve algorithms for identifying particles at the LHC.

Genesis of GAMBIT

The GAMBIT (Global and Modular Beyond-the-Standard-Model Inference Tool) Collaboration can trace its origins back to the 2012 International Conference on High Energy Physics in Melbourne, Australia, where the discovery of the Higgs boson was announced via a live video link to CERN in Geneva. Celebrating in the bars on the south bank of the Yarra river, a group of us began a series of spirited discussions about how to find new physics and solve the dark-matter problem with software.

Martin White is a particle astrophysicist and Australian Research Council Future Fellow at the University of Adelaide, e-mail martin.white@adelaide.edu.au, and **Pat Scott** is an STFC Rutherford Fellow and Lecturer in fundamental physics at Imperial College London, e-mail p.scott@imperial.ac.uk. They are writing on behalf of the GAMBIT Collaboration, which Scott leads and White co-leads (gambit.hepforge.org).

What's next?

- Lots of studies of new physics models
- Cosmology extension
- Axion study has started
- Am very happy to help new Australian users get started
  - would particularly like a CoEPP-assisted GAMBIT composite Higgs study
- We also have some promising engagement opportunities
  - am working with Institute of Photonics and Advanced Sensing on cancer diagnosis techniques